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Beyond patch spraying: site-specific weed management with several herbicides

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Abstract Site-specific weed management can include both limiting herbicide application to areas of the field where weed pressure is above the economic threshold (patch spraying) and varying the choice of herbicide for most cost-effective weed control of local populations. The benefits of patch spraying with several, postemergence herbicides in irrigated corn were evaluated in simulation studies using weed counts from 16 fields. Patch spraying with one, two or the number of herbicides that maximized net return for a field was simulated. With patch spraying of one herbicide, the average area of a field left untreated is 34.5%. Net return increases by \$3.09 ha^{-1} compared to a uniform application without decreasing crop yield. Additional herbicides increase the average benefits with just 4% more of the field treated. With two herbicides, the increase in net return is almost tripled and herbicide use is reduced nearly 10-fold compared to patch spraying with one herbicide, and weed control is better than the uniform application in 10 fields. Using more than two herbicides for patch spraying further reduces weed escapes, but herbicide use is greater than a uniform application in 10 fields. Growers might be more willing to adopt patch spraying if more than one herbicide is used in a field.

Keywords Weed management decision model · Economic threshold · Crop yield loss · Net return · Spatial distribution · Weed patches

Introduction

Site-specific weed management is a strategy of varying weed management within a field to match the variation in density and composition of the weed population. The motivation for site-specific weed management has been to reduce herbicide use, and the focus of research has been patch spraying. Weed management is matched to the variation in weed density so that areas with few weeds are left untreated. These are typically areas with a weed density

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below the economic threshold. Analyses and field experiments have shown herbicide use may be reduced typically by 20–60% in a variety of crops (Gerhards et al. 1997; Johnson et al. 1995) With more sophisticated sprayers, patch spraying has evolved to the intermittent spraying of full and reduced rates of herbicide in response to weed density to reduce herbicide use further or to address growers' concerns about seed production by weeds left in the field (Rider et al. 2006; Timmermann et al. 2003; Tredaway-Ducar et al. 2003; Williams et al. 2000). In the second case, no areas of the field are left untreated. However, the distributions of individual species in a field do not usually coincide and the species present vary among patches. Control might be more cost-effective with several herbicides when local weed populations vary within fields. Technology for patch spraying now is sufficient for site-specific weed management with several herbicides applied in a single pass across a field (Gerhards and Oebel 2006).

There have been two approaches to prescribing several herbicides for a single field from a map of the weed population in the field (Gerhards and Oebel 2006; Nordmeyer 2006). The simplest approach is to identify two or more groups of species to target with different herbicides in a field and then independently create a patch spraying application map for each herbicide. A common example is the targeting of broadleaves and grasses with different herbicides. The second approach relies on weed management decision models. A field is divided into subunits and the herbicide that maximizes net return is recommended for each subunit (Lamastus-Stanford and Shaw 2004; Wilkerson et al. 2004). Prescribing management is easier with herbicides selected for predefined groups of weeds. However, if there is a herbicide that effectively controls species in more than one predefined group, patch spraying might not be more cost-effective than a uniform application. The second approach of maximizing net return for each subunit ensures that when weed control with several herbicides is recommended, it is more cost-effective than a uniform application. A uniform application would be recommended if one herbicide maximizes net return for the field when used for all subunits.

The benefits of prescribing site-specific weed management with several herbicides to maximize net return for a field in soybean were evaluated in simulation studies using weed counts observed at several locations within fields and a weed management decision model (Lamastus-Stanford and Shaw 2004; Wilkerson et al. 2004). Site-specific management was simulated with treatments selected independently for each sampling location and with no limit on the number of herbicides that could be recommended for a field. The recommended treatment for a location maximized the net return based on the weed count at that location. No herbicide was an option for a location. Uniform management was simulated by Wilkerson et al. (2004) as the treatment that maximized total net return for the field if it was used on every sampling location. By contrast, Lamastus-Stanford and Shaw (2004) used the treatment that maximized net return for an average weed population calculated for the field. This population consisted of all species in the field with the density of each equal to the average of the weed counts of all sampling locations. The average net gain from site-specific weed management was \$13 ha^{-1} in both studies for conventional soybeans. However, herbicide use increased rather than decreased in some fields (Wilkerson et al. 2004). In fact, herbicide use and cost, percentage yield loss and weed escapes could all increase or decrease with patch spraying of two or more herbicides because herbicides differ in efficacy and amount of active ingredient.

Site-specific weed management with several herbicides or herbicide combinations in a field will require more complicated and expensive technology, and more management time than patch spraying. The cost will increase with the number of herbicides used in a field. This raises the question—will the benefits justify the costs? Therefore, the objective of this research was to investigate the benefits of using two or more herbicides for site-specific weed management compared to patch spraying with one herbicide and a uniform herbicide application. This was done by simulating site-specific management with one, two or an unlimited number of herbicides and a uniform herbicide application in irrigated corn fields.

Methods and materials

The benefits of postemergence site-specific weed management with several herbicides in irrigated corn were evaluated by simulating the outcomes of management using weed counts from 16 corn fields in eastern Colorado, USA and a weed management decision model. A uniform application (UN) and patch spraying with one (P1) or two (P2) herbicides in a field or with no limit on the number of herbicides for a field (PX) were simulated. The recommended herbicides for these patch spraying strategies and uniform management were selected to maximize net return for a field.

Weed counts

Weed counts from two different experiments in eastern Colorado were used to represent the weed populations in irrigated corn fields. In both experiments, weeds were identified and counted by species in a 0.18 m band over 1.5 m of a crop row just prior to post-emergence weed management (22–29 days after planting). In the first experiment (Wiles and Schweizer 1999), weeds were counted in four fields in 1993 (fields 1–4; Table 1) and a different set of four fields in 1994 (fields 5–8). There were 1225 sample locations on a 7.6 m square grid in an 8.1 ha block of each field. In the second experiment (Wyse-Pester et al. 2002), weeds were counted on sampling grids with a different grid interval from 1997 to 2000 in two additional fields. These fields were 71 ha (fields 9–12) and 53 ha (fields 13–16). For the simulations, I used sampling locations selected to approximate a 25 m square grid throughout each field. This resulted in 181–191 locations in the larger field and 133–145 locations in the smaller field depending on the year.

Simulation model

A modified version of WeedSite software (Wiles et al. 2007) was used to select the recommended treatments for uniform and site-specific weed management and to predict the outcomes for each field. This program predicts outcomes of site-specific weed management from hand drawn weed maps. The outcomes predicted are net return from weed management, area of the field not treated, herbicide use and cost, yield loss from weed competition and weeds left in the field. The program incorporates a validated weed management decision model for irrigated corn in Colorado (Lybecker et al. 1991; Wiles et al. 1996) and is described in detail in Wiles et al. (2007).

A WeedSite user draws the weed patches in a field and selects the resolution of patch spraying to simulate site-specific weed management. To use WeedSite for the simulations, sampling locations were individual patches in a field and the resolution of patch spraying was a sampling location. The herbicides for uniform weed management and the three site-specific weed management strategies were selected to maximize net return for the field. For uniform management, this was the single herbicide that maximized total net return across all sampling locations. There was one herbicide for P1 and two for P2. For P1, the herbicide that was selected maximized net return for the field when no herbicide or that one

Table 1 Weed counts for 16 fields used for simulating site-specific weed management

Field	Weed-free area (% of field)	Broadleaf			Grass		
		Number of species	Density[a] (plants m^{-1})	Area infested (% of field)	Number of species	Density (plants m^{-1})	Area infested (% of field)
1	8.0	7	7.19	90.0	3	1.48	39.4
2	2.4	8	3.14	87.3	4	3.05	88.2
3	81.5	8	1.14	18.4	1	0.01	0.1
4	4.8	9	7.57	94.3	3	0.21	19.0
5	3.0	10	2.16	81.8	2	1.70	77.1
6	0.5	10	15.31	99.3	4	1.14	51.3
7	48.1	7	2.63	41.8	3	0.52	21.1
8	0.1	10	7.49	99.1	3	5.07	77.4
9	50.3	6	5.32	43.4	3	1.37	20.1
10	64.9	5	1.13	30.4	3	0.90	11.0
11	70.3	4	1.40	21.4	2	1.06	12.6
12	1.7	6	13.30	97.8	4	2.53	20.6
13	29.7	6	8.27	69.0	1	0.15	5.5
14	0.7	7	26.59	99.3	2	0.19	15.2
15	4.5	4	6.73	95.5	3	0.19	14.2
16	15.9	5	3.59	84.1	2	0.09	9.1

[a] Plants per meter of crop row

herbicide was selected for a sampling location. For P2, the two herbicides that were selected maximized net return for a field when one of the two herbicides or no herbicide was selected for a sampling location. For PX, net return for the field was maximized without a limit on the number of herbicides. Any one of the herbicides, or no herbicide, was selected for each sampling location.

Net return was calculated from the expected crop price and expected yield with no weeds, herbicide costs and predicted percentage yield loss from weeds not controlled by the herbicide (Lybecker et al. 1993):

$$NR = P \cdot Ywf \cdot (1 - Yldloss) - Cost,$$

where P is the expected crop selling price (\$ kg^{-1}), Ywf is the expected yield if the crop is weed-free (kg ha^{-1}), $Yldloss$ is the proportional yield loss from weed competition and $Cost$ is the cost of herbicide, adjuvant and application (\$ ha^{-1}). Yield loss was calculated from weed density, percentage of the weeds of each species killed by the herbicide and ratings of how well each species competed with the crop. The relationship between weed competition and crop yield loss was based on an assumption that the weeds emerge with the crop and are controlled at the optimal time (Lybecker et al. 1993). Also, a maximum yield loss of 80% was assumed.

$$Yldloss = \text{ Minimum } \left\{ 0.0023252 + 0.00004156 \cdot \sum_{i=1}^{n} (CIi \cdot wi \cdot (1 - Effi)), 0.80 \right\},$$

where w_i is the number weeds of species i in a meter of crop row (plants m^{-1}), CI_i is the competitive index for weed species i and Eff_i is the percentage of weeds of species i killed.

Competitive indices were assigned to weed species based on expert opinion. Assuming that sunflower (*Helianthus annuus*) is the most competitive weed (Lybecker et al. 1993), its competitive index is one. Examples of other indices are 0.85 for pigweed (*Amaranthus* spp.), 0.4 for nightshade (*Solanacae* spp.), 0.8 for lambsquarters (*Chenopodium album*), 0.55 for barnyardgrass (*Echinochloa crus-galli*) and 0.4 for green foxtail (*Setaria viridis*) and longspine sandbur (*Cenchrus longispinus*).

The evaluations included 19 possible herbicides. Possible herbicides and the efficacy and cost of herbicides were based on information in the Colorado and Nebraska Weed Management Guides (Beck et al. 2003; Gaussoin et al. 2005). I used a herbicide application cost of \$12.35 ha^{-1}, expected weed-free yield of 10,087.5 kg ha^{-1} and a crop selling price of \$0.1 kg^{-1} for the simulations. Additional costs for site-specific weed management, such as sampling, were not included.

Results and discussion

Weed pressure and uniform control

Weeds were widespread in most fields and weed populations were dominated by a few species. From 0.1% (field 8) to 81.5% (field 3) of the sampling locations in a field were weed-free (Table 1). The average was 24.2%, but less than 10% of the field was weed-free in nine fields and only five fields had 48% or more weed-free sampling locations. Grasses were less abundant, but more widespread than broadleaf weeds. The infested area and density of grasses and broadleaves were almost equal in one field (field 2). In the other fields, there were more broadleaf than grass weeds. Grass density was <1% of broadleaf density in seven fields.

There were 4–10 broadleaf weed species and one to four grass weed species in a field (Table 1), but only 1–6 species comprised 80% of the weed density in a field (data not shown). The predominant broadleaf weed in all fields was pigweed (*Amaranthus* spp.) or nightshade (*Solanacae* spp.), and both occurred in all fields (data not shown). Foxtail (*Setaria* spp.) was present in 15 of the fields, but longspine sandbur (*Cenchrus longispinus*) or barnyardgrass (*Echinochloa crus-galli*) was each the predominant grass in eight fields (data not shown). With the similar species mix in these 16 fields, one of just five different herbicides is recommended for a uniform herbicide application (Table 2). Carfentrazone-ethyl is recommended for 10 of the fields.

Benefits of patch spraying

The area of the field left untreated with the typical patch spraying method (P1) ranges from less than 1% to more than 90% (Table 2), with an untreated average for the 16 fields of 34.5% (Table 3). The average gain in net return with P1 compared to UN is \$3.09 ha^{-1} that results primarily from spending less on herbicide. Weed escapes increase by an average of 0.02 plants m^{-1} of row.

The area of the field not sprayed with P1 is consistent with other simulation and field experiments of patch spraying for corn (Johnson et al. 1995; Williams et al. 2000). However, other outcomes are difficult to compare with previous results because most

Table 2 Herbicides and percentage of the field treated for site-specific weed management

Field	Strategy	No herbicide	Carfentrazone-ethyl	Mesotrione	Rimsulforun + thifensulfuron	Rimsulforun + nicosufuron + atrazine	Foramsulfuron + iodsulfuron-methyl-sodium	Bromoxynil + atrazine	Flumetsulam + clopyralid	Dicamba	2,4 D	Bromoxynil
1	P1	16	**85**									
	P2	15	**67**				18					
	PX	14	**59**		16	*	8	2			*	*
2	P1	22					**78**					
	P2	10			56		**34**					
	PX	7	23		43	*	**27**	*			*	
3	P1	93	**7**									
	P2	93	**6**								1	
	PX	93	**6**								1	
4	P1	11	**89**									
	P2	11	**86**					3				
	PX	11	**85**		1		*	3	*	*	1	*
5	P1	20			**80**							
	P2	12	43		**46**							
	PX	12	39		**42**	1	6	*		1	1	
6	P1	4						**96**				
	P2	2	46					**53**				
	PX	1	31		4	4	0	**40**		5	8	7
7	P1	76	**24**									
	P2	72	**19**		9							
	PX	72	**18**		9	*	*	*			*	*
8	P1	6				**94**						
	P2	1	52			**47**						
	PX	1	46		7	**39**	3	1		*	1	3

Table 2 continued

Field	Strategy	No herbicide	Carfentrazone-ethyl	Mesotrione	Rimsulforun + thifensulfuron	Rimsulforun + nicosufuron + atrazine	Foramsulfuron + iodsulfuron-methyl-sodium	Bromoxynil + atrazine	Flumetsulam + clopyralid	Dicamba	2,4 D	Bromoxynil
9	P1	80					20					
	P2	57	**26**		18							
	PX	57	**24**		15		2	2		1		
10	P1	76			24							
	P2	73	**20**		7							
	PX	73	**19**		6		1				1	
11	P1	85	**15**									
	P2	81	**13**		7							
	PX	81	**13**		7							
12	P1	3					**97**					
	P2	2	53		45							
	PX	2	42		38		**3**	14				
13	P1	35	**66**									
	P2	35	**55**		10							
	PX	35	**50**		10			5			1	
14	P1	1						**99**				
	P2	1			41			**58**				
	PX	1	27	2	33	1	1	**35**				
15	P1	5	**95**									
	P2	5	**67**		28							
	PX	5	**66**		26		1	2				

Table 2 continued

Field	Strategy	No herbicide	Carfentrazone-ethyl	Mesotrione	Rimsulforun + thifensulfuron	Rimsulforun + nicosufuron + atrazine	Foramsulfuron + iodsulfuron-methyl-sodium	Bromoxynil + atrazine	Flumetsulam + clopyralid	Dicamba	2,4 D	Bromoxynil
16	P1	19	**81**									
	P2	19	**75**		6							
	PX	19	**74**		6					1		

The herbicide in bold for a field is the herbicide selected for a uniform application and * indicates less than 0.5% of a field was treated with that herbicide. Herbicide rates are shown in the table

Herbicides with rates: 7 g ha^{-1} carfentrazone-ethyl; 105 g ha^{-1} mesotrione; 12 g ha^{-1} rimsulfuron + 6 g ha^{-1} thifensulfuron; 13 g ha^{-1} rimsulfuron + 13 g ha^{-1} nicosulfuron + 851 g ha^{-1} atrazine; 26 g ha^{-1} foramsulfuron + 2 g ha^{-1} iodsulfuron-methyl-sodium; 350 g ha^{-1} bromoxynil + 700 g ha^{-1} atrazine; 39 g ha^{-1} flumetsulam + 126 g ha^{-1} clopyralid; 413 g ha^{-1} dicamba; 644 g ha^{-1} 2,4 D; 700 g ha^{-1} bromoxynil

Table 3 Comparison of site-specific weed management with a uniform herbicide application for 16 fields

Site-specific strategy	Net change from a uniform herbicide application													
	Area not treated (% of field)		Net return ($ ha^{-1})		Herbicide cost ($ ha^{-1})		Herbicide use (g active ingredient ha^{-1})		Yield loss (%)		Broadleaf escapes[b] (plants m^{-1})		Grass escapes (plants m^{-1})	
	Mean	SD[a]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
P1	34.5	34.4	3.09	2.79	−3.52	3.09	−8.5	14.3	0.05	0.22	0.05	0.04	−0.03	0.15
P2	30.4	32.9	8.43	4.84	−7.76	8.92	−83.9	179.5	−0.07	0.80	0.07	0.29	−0.11	0.30
PX	30.1	33.1	9.69	5.51	−7.82	8.85	−80.0	227.7	−0.20	0.80	0.02	0.29	−0.13	0.31

A positive number indicates the value was greater for patch spraying than the value for a uniform application

[a] Standard deviation

[b] Plants per meter of crop row

studies compared patch spraying and uniform application of the same herbicide. In this study, herbicides were selected to maximize net return for a field. It is possible that the herbicide that maximizes net return for patch spraying is different from the herbicide that maximizes net return for a uniform application. For two fields (9 and 10), a more expensive herbicide is selected for P1 than UN. Nevertheless, herbicide cost is still reduced compared to UN because over 50% of these two fields was weed-free (Table 1). The different herbicides selected for P1 and UN are the reason for the small decrease of 0.03 grass escapes per meter of crop row (plants m^{-1}) with P1.

Additional herbicides increase the average benefits of patch spraying with just a small increase of 4% in the area of the field treated. The increase in net return almost trebles compared to P1, herbicide use is reduced nearly 10-fold and the saving in the cost of herbicide doubles (Table 3). The average net gain is \$8.43 ha^{-1} for P2 primarily due to a decrease in herbicide costs (\$7.76 ha^{-1}). The net gain is \$1.26 ha^{-1} more for PX than P2. The additional gain with PX compared to UN is due primarily to an increase in crop yield of 0.13% of weed-free yield.

The most significant benefit of patch spraying with more than one herbicide might be improved control of the weed population. Weed escapes are expected to increase with patch spraying because areas of the field are left unsprayed. However, average net escapes decrease by 0.04 plants m^{-1} with P2 and 0.11 plants m^{-1} with PX. Both broadleaf and grass escapes are reduced.

Many of the additional herbicides are used on just a small portion of the field for both P2 and PX. The area treated with a single herbicide varies from 0.1% to 86% of a field, with an average of 34.8% of a field treated with a single herbicide for P2 and 13.6% for PX. At least three herbicides, together with leaving some of the field untreated, are recommended for the maximum benefit from patch spraying for all but two of the fields (Table 2). These fields, 3 and 11, had the most weed-free areas (Table 1). The maximum number of herbicides recommended is eight, and this is for fields 4, 6 and 8, but many herbicides are recommended for less than 1% of the field. Excluding the two most widely used herbicides in a field, a single herbicide is recommended for at most 26.9% of a field and the average area is just 2.8% of a field. Spraying herbicide on such small areas of the field would be likely to be expensive.

Variation in site-specific weed management among fields

Outcomes of site-specific weed management vary among fields in these simulations, as has been observed in other studies (Lamastus-Stanford and Shaw 2004; Wilkerson et al. 2004). Distributions of net change compared to a uniform application in the fields are illustrated using percentile box plots with quantiles of 12.5% (Fig. 1). Outcomes are more variable across fields with P2 and PX than with P1, and most distributions of net change for P2 and PX include both negative (smaller than the value for UN) and positive (larger than the value for UN) values of net change. By contrast, outcomes for P1 compared to UN are more consistently 'bad' or 'good' across fields.

Weed escapes and crop yield loss with P1 decrease compared to UN in all but the two fields (9 and 10) for which different herbicides are used for P1 and UN. Distributions of net yield loss and net escapes are similar for P2 and PX. These distributions have greater variability than P1 (Fig. 1). Weed escapes and crop yield decrease in 65% of the fields with P2 and PX, but the increases in yield loss and weed escapes with P2 and PX are larger than most of the increases with P1. The maximum increases for both P2 and PX are twice the maximum increase of yield loss (0.54%) and weed escapes (0.27 plants m^{-1}) as that for P1.

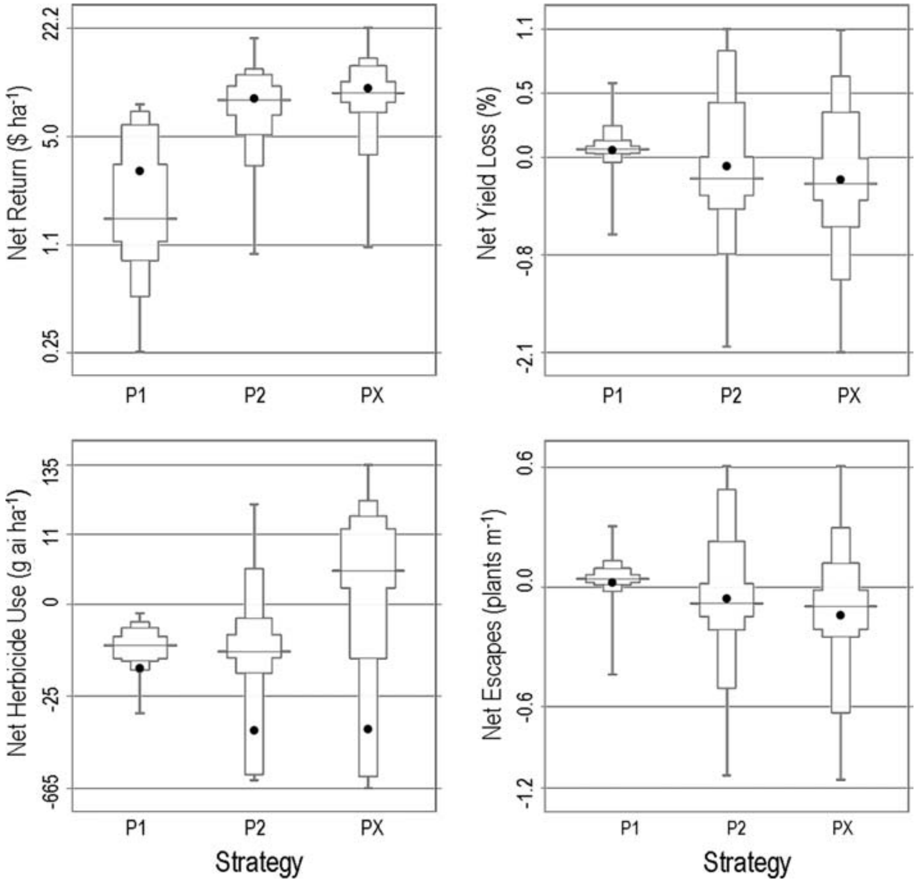


Fig. 1 Box plots of the change in net return, herbicide use, crop yield loss and weed escapes with site-specific weed management compared to a uniform application for 16 fields. Positive numbers indicate a higher value for patch spraying than a uniform application. Some results are plotted on a log or hyperlog scale

Herbicide use among the fields is a distinguishing outcome among the patch spraying strategies. Herbicide use decreases by at least 0.4 g ha^{-1} in all fields for P1, but increases in some fields with P2 and PX. In addition, average herbicide use is similar with P2 and PX, but the average for PX is the result of large decreases in fields 6, 8 and 14 which outweigh increases in other fields. Herbicide use increases with PX compared to UN in 10 of the fields, but increases in only three fields for P2. There are large decreases in 20% of the fields for both P2 and PX (402–665 g ha^{-1}), and these are much larger than the maximum decrease in herbicide use with P1 (46 g ha^{-1}). The largest decreases and increases in herbicide use are with PX because of the greater variety of herbicides recommended. This strategy includes the use of 10 different herbicides (Table 2), whereas only five herbicides are used for P1 and six herbicides are used for P2.

Patch spraying is promoted as a strategy to reduce herbicide use. The use of two or more herbicides for patch spraying would be likely to be a less expensive method for a grower to reduce herbicide use over time or across a farm compared to patch spraying with the one herbicide. However, it cannot be assumed that herbicide use will be reduced in every field and the area of the field that would not be sprayed would be a less reliable indicator of the reduction in herbicide use with patch spraying with two or more herbicides compared to patch spraying with one herbicide. If the goal is to reduce herbicide use in every field, herbicide use would have to be calculated when patch spraying with two herbicides is recommended based on maximizing net return from a field.

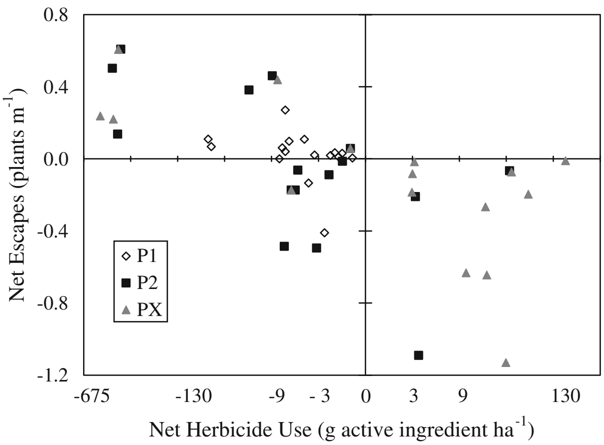
Trade-offs with several herbicides for site-specific weed management

The typical tradeoff for patch spraying with a single herbicide, more weeds for less herbicide, occurs in fewer than half of the fields for both P2 and PX (Fig. 2). Unlike patch spraying with a single herbicide, patch spraying with several herbicides can improve weed control in a field. Consequently, patch spraying with several herbicides could be a useful weed management strategy depending on the relationships among herbicide use, weed control and net return.

The best possible outcome from patch spraying is to use less herbicide and leave fewer weeds in the field. This occurs in seven fields for P2 and in just one field with PX. This also occurs twice with P1 when a different herbicide is used for patch spraying than for a uniform application. Weed escapes are reduced by an average of 0.21 plants m^{-1} in the seven fields for P2. In all but one case for P2, crop yield loss is reduced as well (data not shown). Other studies of site-specific use of several herbicides within fields indicated the potential to increase net return, decrease crop yield loss and improve weed control compared to a uniform application (Lamastus-Stanford and Shaw 2004; Wilkerson et al. 2004). The reduction in herbicide use when weed control is improved might be expected to be related inversely to the improvement of weed control. This was not so; the reduction in herbicide use in combination with fewer weed escapes with P2 and PX is similar to the reduction with P1 that occurs with an increase in weeds escapes. For growers who are concerned about seed production by weeds left in the field, the improved weed control could outweigh the small economic benefit or additional costs of site-specific weed management intended to reduce herbicide use.

The most frequent outcome with PX (10 fields) is the use of more herbicide and control of more weeds compared to a uniform application. Herbicide use increases by up to 134 g ha^{-1} and weed escapes are reduced by up to 1.13 plants m^{-1}. The improvement in

Fig. 2 Change in herbicide use and weed escapes with site-specific weed management compared to a uniform application. Positive numbers indicate a higher value for patch spraying than a uniform application



weed control is not strongly related to the increase in herbicide use. In fact, the largest increase in herbicide use with P2 or PX occurs with the smallest decrease in number of weeds left in the field (0.01 plants m^{-1}). The improved weed control is not necessarily costly either. The largest increases in net return are associated with an almost equal number of incidents of increases and decreases in weed escapes for P2 and PX (Fig. 3).

The change in grass and broadleaf weed escapes with patch spraying compared to UN is shown in Fig. 4. The shaded area in the graph indicates increases in total weed escapes compared to a uniform application. With several herbicides for patch spraying, control of grasses is improved more than that of broadleaves when the total weed escapes decrease (points in the unshaded area of the graph), and in some fields this was so even when total weed escapes increased (points in the shaded areas of the graph). When both broadleaf and grass weeds are present in a field, the approach of patch spraying with several herbicides, used in this research, could be a more cost-effective method than independent patch spraying of both a grass herbicide and a broadleaf herbicide in a field.

Patch spraying with two or three herbicides in a single pass through a field is technically feasible. Limiting the number of herbicides used for site-specific weed management in a

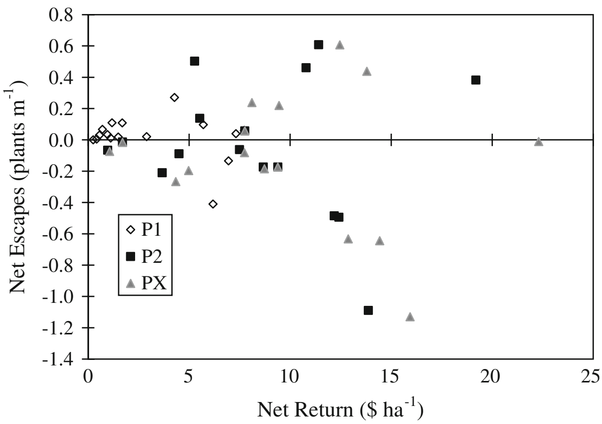


Fig. 3 Change in weed escapes and net return with site-specific weed management compared to a uniform application. Positive numbers indicate a higher value for patch spraying than a uniform application

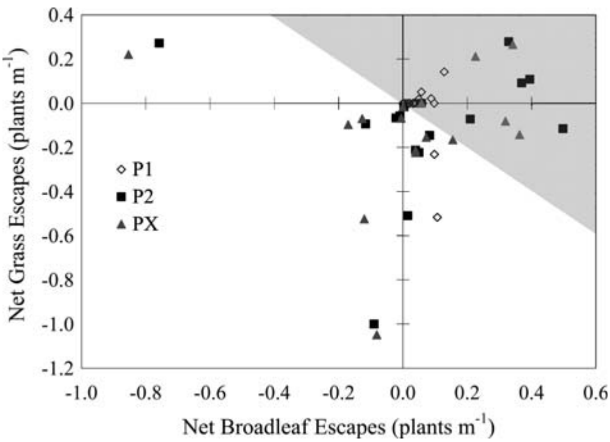


Fig. 4 Change in grass and broadleaf weed escapes and net return with site-specific weed management compared to a uniform application. Positive numbers indicate a higher value for patch spraying than a uniform application. The shaded area indicates combinations that would result in an increase in weed escapes in a field compared to a uniform application

field to two or three simplifies the complex task of choosing the appropriate combination of herbicides for a field. Most studies of patch spraying with several herbicides have not had a limit on the number of herbicides used within a field. Is two or three herbicides enough for an improvement over patch spraying with one herbicide? These results indicate that there might be little benefit in using more than two herbicides within a field when the primary goal is to reduce herbicide use. Increases in herbicide use become more likely with more than two herbicides. For growers who are more concerned about weeds left in the field than about herbicide use, using more than two herbicides could be a better strategy. Greater improvement in weed control is more likely when more than two herbicides are used.

Conclusions

The results of this study are similar to those of other studies in that the average net return of site-specific weed management is small. The additional return might not cover the additional management costs. Patch spraying of weeds cannot be recommended enthusiastically to growers based on average net return among fields. However, two important characteristics of site-specific weed management are illustrated in this study. First, outcomes from site-specific weed management are very variable among fields. Second, the use of several herbicides within a field can increase the net return and address growers' concerns about weeds left in the field. Site-specific weed management might be more acceptable to growers if several herbicides are used within a field in addition to leaving some areas untreated, and if we learn to identify characteristics of weed populations in fields for which site-specific weed management will be most beneficial. Growers will need decision models to help with the complex task of selecting the right combination of herbicides for a field.

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